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Failure At and Near Interfaces

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This report covers results of research addressing the failure behavior of bonded materials at and near the interface in support of structural integrity methodology of the failure response of solid propellant rocket motors under storage and operating conditions. Interfacial failure has been investigated both experimentally and analytically. Experiments determined the propagation of a crack away from an interface and established the direction and onset of crack propagation. The analytical studies corroborated this behavior essentially very well, except that the small deformation analysis was found to be devoid of uniqueness, in that a size parameter is needed to closely correlate the experiments with the analysis. As a result detailed large deformation analyses were also performed that eliminate much of the uniqueness problem, but leads to crack propagation in one direction only. It is concluded that a true fracture problem is a mix between small and large deformation formulations. These formulations depend on how large the growth steps of crack propagation are relative to the size of a small zone of nonlinear material response around the crack tip vis-a-vis the region of relatively small strain farther from the crack tip.

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CONTENTS

ABSTRACT

This report covers results of research addressing the failure behavior of bonded materials at and near the interface in support of structural integrity methodology for the failure response of solid propellant rocket motors under storage and operating conditions. Interfacial failure has been investigated both experimentally and analytically. Experiments determined the propagation of a crack away from an interface and established the direction and onset of crack propagation. The analytical studies corroborated this behavior essentially very well, except that the small deformation analysis was found to be devoid of uniqueness, in that a size parameter is needed to closely correlate the experiments with the analysis. As a result detailed large deformation analyses were also performed that eliminate much of the uniqueness problem, but leads to crack propagation in one direction only. It is concluded that a true fracture problem is a mix between small and large deformation formulations. These formulations depend on how large the growth steps of crack propagation are relative to the size of a small zone of nonlinear material response around the crack tip vis-a-vis the region of relatively small strain farther from the crack tip.

EXECUTIVE SUMMARY

This program has dealt with the establishment of criteria governing propagation of a crack located at an interface away from the same into one or the other of the two adherends. The application of the results impact a range of engineering problems. Among these problems the most important ones are interfacial bond failure in solid propellant rocket motors (propellant-liner-insulation), interfacial failure in electronic (chip) components, as well as a large variety of adhesion problems. While certain material such as electronic chips warrant, to some degree, the use of linear elastic analyses, the same cannot be said universally when materials with rubber-type characteristics are involved. As a consequence, considerable attention has been devoted to those aspects of interfacial fracture that interact with the large deformation capability of materials.

Summarized here briefly are the numerous publications detailing fully the accmplishments achieved under this grant. It is not necessary to repeat these details here, except for drawing attention to the major consequences of this work. Although the motivation for this work came from the application of fracture mechanics to solid propellant rocket failures, the results obtained under this grant also have strong implications for bond systems involving considerably different adherend materials.

Results from experimental studies:

Crack propagation away from an interface depends on the loading applied far from the nterface crack. Basically, two issues arise:

a) If one knows the physical properties and fracture description for each one of the adherends separately, how does this information translate into the crack propagation behavior when the crack runs along the interface?

b) In what direction does the crack propagate away from the interface under complex loading?

There is, in general, both normal loading and shear loading present at the crack tip, even if the distant loading is prescribed totally in terms of interface-normal tractions. This produces a crack tip-near stress field that is characterized in terms of what has become known as "load mixity", which becomes the parameter that largely governs the orientation of the crack growth.

Results: a) There is a small but finite range of combined local (normal and shear) loading for which the crack propagates along the interface. Outside of that range the crack will grow into either one of the two solids, depending on the direction of the shear parallel to the interface [1,2].

b) If one knows the properties, and, in particular, the rate dependent fracture function for either one of the two (monolithic) adherends, one can compute the corresponding rate dependent portion of the interfacial fracture energy by a suitable averaging process [3]. The absolute magnitude of the interfacial fracture energy is determined by the intrinsic interfacial bonding of the two materials.

This latter result was established by casting two polymers of a similar molecular constitution on top of each other before the first one was totally cured, so that the residual chemical activity allowed chemical bonding without destroying the planarity of the interfacial surface.

Results for the experimental studies are summarized extensively in the thesis by John M. Bowen, entitled "An Experimental Investigation of Fracture at a Bimaterial Interface", (1992) [4].

Results from analytical studies:

Analyses performed under this grant part into two types:

a) Infinitesimal deformation analyses, and

b) Large deformation analyses.

The large deformation studies were introduced because the small deformation analyses, normally employed by researchers in this field, led to a problem of non-uniqueness.

Small deformation analysis: Crack propagation is oriented such that the energy released is a maximum with respect to the particular crack orientation relative to the interface. When one computes this maximal energy released the analysis requires the specification of a length parameter that is not part of the analysis. As a result, the computations do not yield unique results, but, in contrast to the fracture description for monolithic solids, depend on the magnitude of the crack extension length. This parameter can only be determined from experiments, which were done. However, its magnitude, on the order of a fraction of a millimeter for the material studied, did not provide any clue as to its physical origin or meaning [5,6].

Apart from this anomaly the experimentally determined crack kinking behavior was rather well corroborated by the experiments.

Large deformation analysis: In order to understand the anomalous situation with the size parameter required by the small deformation analysis —which, however, does not appear naturally in the linearized analysis— we turned to large deformation considerations with the expectation that in the limit of small loading the large deformations would revert back to small deformations and thus provide a limit process from which one might understand the incompleteness and inconsistency in the small deformation results.

That expectation was fulfilled, inasmuch a finite deformation analysis showed the development of a zone at the crack tip in which large deformations were dominant. This "nonlinear zone" decreases continuously with decreasing load, and thus achieves zero size in the limit of vanishing deformations, which also corresponded to the unloaded solid [7].

Whether the crack branching corresponds to the linearized analysis depends on the size of the crack growth step relative to that of the nonlinear zone. If the crack growth occurs by a step size that is small compared to the nonlinear zone size, then the large deformation analysis applies. If, however, the crack advance is larger than the nonlinear zone size then the linearized results apply.

In the former case—large deformation analysis applies—the crack propagates along a unique plane that makes a fixed small angle with the interface, regardless of the magnitude of the loading on the interface. Load mixity is not important then. When the two materials become the same—fracturing monolithic solid—the crack always propagates along the original plane of the crack.

Another result of the large deformation analysis that is both interesting and important is the following. In the linearized analysis there appears a singular term in the expansion of the stress field around the crack tip (monolithic or bonded solid with an interface). For the large deformation problem this is no longer true in that multiple singular terms may arise [8,9,10].

The analytical studies have been documented also in a Ph.D. thesis by Philippe H. Geubelle, and is entitled "Nonlinear Effects in Interfacial Fracture", (1993) [11].

Persons participating:

Besides consistent contributors to the program, there have been several individuals who aided on a more passing basis in the execution of this research. In the first group we list:

W.G. Knauss	Professor of Aeronautics and Applied Mechanics—P.I.
J.M. Bowen.	Received his Engineering Degree in Aeronautics in 1992 presently attending Harvard Business School for further studies.
P. H. Geubelle	Received his Ph.D. in 1993; performed post doctoral research at Harvard for a year and is now Assistant Professor of Aeronautics at the University of Illinois, Urbana/Champaign

Additional supporting staff and students were:

Eli Mazor
Xiang-Ho Zhang
Carl Schultheisz
Carlos Shultz
Guillaume Vendroux

Publications:

The following publications arose from the research and are referenced above in the appropriate sections of this executive summary. The abstracts from these publications follow.

[1] Bowen, J.M. and Knauss, W.G., "An Experimental Study of Interfacial Crack Kinking" *Experimental Mechanics*, pp. March, 1993, pp 37-43

[2] Bowen, J.M. and Knauss. W.G., "An Experimental Study of Crack Kinking at an Interface", *Advances in Experimental Mechanics and Biomimetics*, ASME AD-**Vol. 29**/AMD-**Vol. 146**, pp. 41-49, 1992. Presented at ASME Winter Annual Meeting, 1992.

[3] Bowen, J.M. and Knauss, W.G., "The Characterization of the Energy of Fracture at or near Interfaces Between Viscoelastic Solids", *Journal of Adhesion*, **Vol. 39**, 1992, pp. 43-59,

[4] Bowen, J.M., "An Experimental Investigation of Fracture at a Bimaterial Interface", Engineering Thesis, GALCIT Report SM 92-24, 1992, California Institute of Technology, Pasadena, California, 91125.

[5] Geubelle, P.H. and Knauss, W.G., "Crack Propagation at and near Bimaterial Interfaces: Linear Analysis", *Journal of Applied Mechanics,* **Vol. 61**, Sept., 1994, pp. 560-566

[6] Geubelle, P.H. and Knauss, W.G., "A Note Related to Energy Release Rate Computations for Kinking Interface Cracks" in press *Journal of Applied Mechanics*, **Vol. 62** (1), 1995 pp 266-267

[7] Geubelle, P.H. and Knauss, W.G., "Crack Propagation in Homogeneous and Bimaterial Sheets under General In-Plane Loading: Nonlinear Analysis", to appear in *Journal of Applied Mechanics*, **Vol. 62**, Sept. 1995, pp 601-606

[8] Geubelle, P.H. and Knauss, W.G., "Finite Strains at the Tip of a Crack in a Sheet of Hyperelastic Material: I. Homogeneous Case", *Journal of Elasticity,* **Vol. 35**, 1994, pp. 61-98

[9] Geubelle, P.H. and Knauss, W.G., "Finite Strains at the Tip of a Crack in a Sheet of Hyperelastic Material: II. Special Bimaterial Cases", *Journal of Elasticity,* **Vol. 35**, 1994, pp. 99-137

[10] Geubelle, P.H. and Knauss, W.G., "Finite Strains at the Tip of a Crack in a Sheet of Hyperelastic Material: III. General Bimaterial Cases", *Journal of Elasticity,* **Vol. 35**, 1994, pp. 139-174

[11] Geubelle, P.H., "Nonlinear Effects in Interfacial Fracture", Ph.D. Thesis, GALCIT Report SM 93-10, 1993, California Institute of Technology, Pasadena, California, 91125.

AN EXPERIMENTAL STUDY OF INTERFACIAL CRACK KINKING

J. M. Bowen and W.G. Knauss

The growth of a crack located at the interface between two linearly elastic solids is investigated experimentally. It is found that the crack may advance by kinking into either of the adherends or by propagating along the interface itself, depending on the applied loading conditions. The experimentally observed kinking behavior is compared with analytical results. Agreement between these results is improved by suitable manipulation of a presumably material characteristic crack-extension length, the origin of which is rooted in the linearized analysis. The influence of material rate effects on the crack-kinking behavior is also investigated.

Experimental Mechanics, March, 1993 pp. 37-43

AN EXPERIMENTAL STUDY OF CRACK KINKING AT AN INTERFACE

J. M. Bowen and W.G. Knauss

The growth of a crack located at the interface between two linearly elastic solids is investigated experimentally. The crack is found to advance by kinking into either of the adherends or by propagating along the interface itself. The experimentally observed kinking behavior is compared with analytical results. The influence of material rate effects on the crack kinking behavior is also investigated to a limited extent.

Advances in Experimental Mechanics and Biomimetics,
ASME AD-**Vol. 29**/AMD-**Vol. 146**, 1992 pp. 41-49

THE CHARACTERIZATION OF THE ENERGY OF FRACTURE AT OR NEAR INTERFACES BETWEEN VISCOELASTIC SOLIDS

J.M. Bowen and W.G. Knauss

The problem of separating two viscoelastic solids of different properties in a time dependent manner is considered. This work is part of a wider study concerned with the time dependent failure of viscoelastic adhesive bonds at and/or near the interface, including propagation of a crack away from the interface. Inasmuch as such a study requires sufficient bond strength to control the orientation of crack propagation, this paper deals with the characterization of interface strength. Following earlier analysis of crack propagation in homogeneous and bimaterial viscoelastic solids, experimental studies concerned with rate dependent fracture at the interface are evaluated in terms of the viscoelastic functions associated with homogeneous fracture of the adherends and a separate interface-intrinsic strength which is determined by the chemistry at the interface. This interface strength multiplies a viscoelastic function, which, for the interface problem, is a combination of the properties of the homogeneous solids. Interface strength on the same order as those of the adherends is achieved.

Journal of Adhesion, **Vol. 39**, 1992 pp. 43-59

AN EXPERIMENTAL INVESTIGATION OF FRACTURE AT A BIMATERIAL INTERFACE

John Murray Bowen,

Engineering Thesis

The growth of a crack located at the interface between two linearly viscoelastic solids is investigated experimentally. It is found that the crack may advance by kinking into either of the adherends or by propagating along the interface itself, depending on the applied loading. For the separation problem, in which crack advance occurs along the bimaterial interface, it is demonstrated that the time-dependent unbonding of the two joined viscoelastic solids follows a rate-dependent fracture process that can be described to a large extent by the viscoelastic properties of the two adherends. Moreover, the strength of the interfacial bond can be characterized in terms of an equilibrium interface-intrinsic fracture energy, the magnitude of which represents the bond strength quantitatively. In particular, interface strength on the same order as those of the adherends is achieved. In contrast to the time-dependent approach developed for the separation problem, the propensity of the interface crack to kink out of the interface upon loading is evaluated in the context of (time-dependent) linearly elastic fracture mechanics. It is demonstrated that crack propagation along the interface occurs for a finite range of load mixity, a phenomenon predicted by linear analysis of the bimaterial joint but absent from the corresponding homogeneous development. Agreement between observed kinking behavior and analytical results is seen to improve by suitable manipulation of a presumably material characteristic length, the origin of which is rooted in the linearized analysis. The influence of material rate effects on the crack kinking behavior is also investigated.

GALCIT Report SM 92-24, 1992

California Institute of Technology, Pasadena, California, 91125

CRACK PROPAGATION AT AND NEAR BIMATERIAL INTERFACES: LINEAR ANALYSIS

P.H. Geubelle and W.G. Knauss

The problem of the growth of a crack located at the interface between two linearly elastic solids is considered when conditions promoting propagation along and/or away from the interface prevail. Both a stress and a maximum energy release rate criterion are examined. It is found that in contrast to the corresponding problem for crack growth in homogeneous solids no unique propagation direction results when continuum considerations prevail alone. Uniqueness is established only upon invoking a presumably material dictated minimum crack extension size. The result for this linearized analysis are compared with experimental observations on kink fracture involving two elastomers of small strain capabilities.

Journal of Applied Mechanics, **Vol. 61,** Sept. 1994 pp. 560-566

A NOTE RELATED TO ENERGY RELEASE RATE COMPUTATIONS FOR KINKING INTERFACE CRACKS

P.H. Geubelle and W.G. Knauss

With the growing importance of composite materials and structures, including packaged electronic (chip) devices, the need to better understand and control failure behavior at and near interfaces has taken on increased engineering significance. In comparison with fracture of homogeneous solids, the (linear) elastic analysis of "brittle" interfacial fracture problems suffers from complications associated with the appearance of a contact zone very close to the tip of the interface crack and with the "oscillatory" character of the near-tip stress distribution. In contrast to homogeneous solids, this stress and deformation field behavior complicates the fracture analysis of the kinking behavior of an interface crack since it makes the usually useful quantity of the energy release rate non-unique when the crack kinks away from the interface.

Journal of Applied Mechanics, **Vol. 62** (1),1995 pp 266-267

CRACK PROPAGATION IN HOMOGENEOUS AND BIMATERIAL SHEETS UNDER GENERAL IN-PLANE LOADING: NONLINEAR ANALYSIS

P.H. Geubelle and W.G. Knauss

The problem of non-coplanar crack propagation in homogeneous and bimaterial sheets is investigated within the framework of the nonlinear theory of plane stress and for the Generalized Neo-Hookean class of hyperelastic solids. The analysis is performed numerically using a boundary-layer approach and the maximum energy release rate criterion. The influence of the large deformation effect on the limiting process associated with the concept of "infinitesimal virtual crack extension" is examined, together with the possible relation between the size of the nonlinear zone and the additional length parameter appearing in the linearized analysis of the interfacial crack propagation problem. As the virtual crack extension is gradually shortened to a size comparable to that of the nonlinear zone, a transition is observed between the non-unique value of the kink angle predicted by the linearized theory and a single "nonlinear" value, which is independent of the crack extension length but also independent of the far-field loading conditions. In the limit of homogeneous properties this angle is zero and is corroborated by experiments on natural rubber undergoing large deformations.

Journal of Applied Mechanics, **Vol. 62**, Sept. 1995 pp 601-606

FINITE STRAINS AT THE TIP OFF A CRACK IN A SHEET OF HYPERELASTIC MATERIAL
I. HOMOGENEOUS CASE

P.H. Geubelle and W.G. Knauss

This paper describes an asymptotic analysis of the strain and stress fields at the tip of a crack in a sheet of incompressible hyperelastic material. The investigations are carried out within the framework of finite elastostatics and for the class of Generalized Neo-Hookean materials. Both the symmetric (mode I) and non-symmetric (mixed-mode) cases are considered. It is shown that the latter situation corresponds locally to a rigid body rotation of the symmetric fields. The effect of the "hardening" parameter on crack tip blunting is investigated analytically and numerically.

Journal of Elasticity, **Vol. 35**, 1994 pp. 61-98

FINITE STRAINS AT THE TIP OF A CRACK IN A SHEET OF HYPERELASTIC MATERIAL
II. SPECIAL BIMATERIAL CASES

P.H. Geubelle and W.G. Knauss

An asymptotic analysis of the strain and stress near-tip fields for a crack in a sheet of Generalized Neo-Hookean materials is presented in this section in a series of three papers. The analysis is based on the nonlinear plane stress theory of elasticity and concerns two special cases of the interface crack problem: in the first situation both components have the same "hardening" behavior; next we investigate the particular case of a sheet of Generalized Neo-Hookean material bonded to a rigid substrate. The transition between the two special cases is studied in detail. The analytical results are also compared with a full-field finite element solution.

Journal of Elasticity, **Vol. 35**, 1994 pp. 99-137

FINITE STRAINS AT THE TIP OF A CRACK IN A SHEET OF HYPERELASTIC MATERIAL III. GENERAL BIMATERIAL CASE

P.H. Geubelle and W.G. Knauss

In this last in a series of three papers, we summarize an asymptotic analysis of the near-tip stress and deformation fields for an interface crack between two sheets of Generalized Neo-Hookean materials. This investigation, which is consistent with the nonlinear elastostatic theory of plane stress, allows for an arbitrary choice, on both sides of the three parameters characterizing this class of hyperelastic materials. The first three terms of the approximation series are obtained, showing the existence of a non-oscillatory of contact-free solution to the interface crack problem. The analytical results are compared with a full-field solution obtained numerically using the finite element code.

Journal of Elasticity, **Vol. 35**, 1994 pp. 139-174

NONLINEAR EFFECTS IN INTERFACIAL FRACTURE

Philippe H. Geubelle

Ph.D. Thesis

The combined effects of material and geometrical nonlinearities on the structure of the near-tip stress and deformation fields are studied in the case of an interface crack in a bimaterial sheet. The problem is analyzed asymptotically and numerically within the framework of the finite strain elastic theory of plane stress. Material-induced nonlinearities are introduced by using the Generalized Neo-Hookean model characterized by three parameters corresponding to the linearly elastic, "yielding" and "hardening" behaviors.

Three bimaterial situations are investigated: (a) both components have similar hardening characteristics, (b) one component is considered as rigid, (c) general bimaterial problem allowing for an arbitrary choice of the six parameters defining the mechanical response. The existence of a non-oscillatory contact-free solution in the vicinity of the crack-tip is confirmed for this class of hyperelastic materials, and the nonlinear effects are quantified by a nonlinear mismatch parameter characterizing the distribution of the (large) deformations on both sides of the interface.

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California Institute of Technology, Pasadena, California, 91125